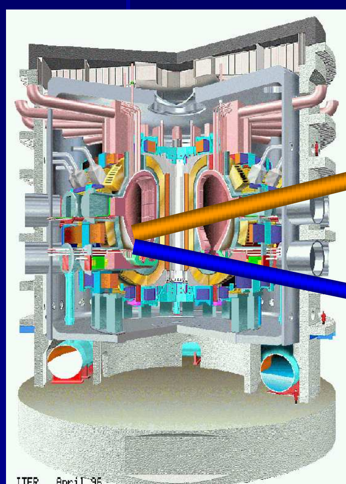
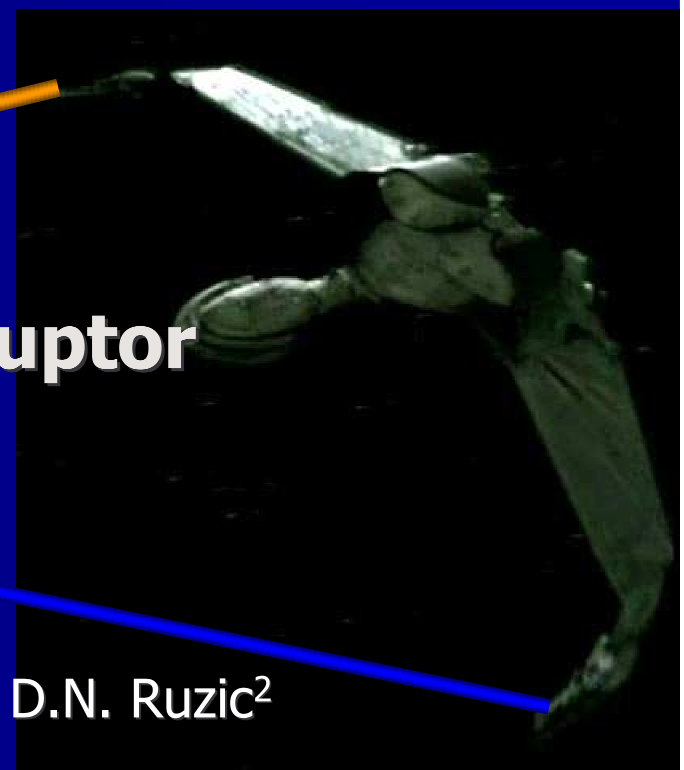
ITER ELM Plasma Simulator

A Promising Component of the US PFC Materials Test Program



or

Mark II Plasma Disruptor



R. Stubbers[1], T.K. Gray[2], B.C. Masters[2], D.N. Ruzic[2]

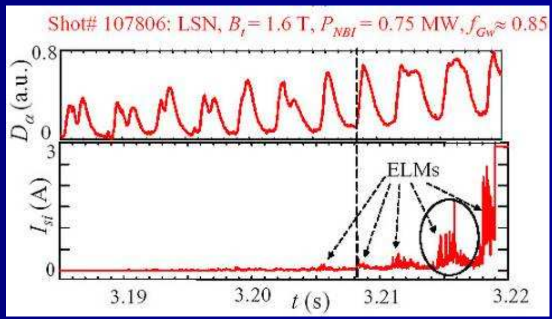
[1]Starfire Industries LLC
[2]University of Illinois, Plasma-Material Interaction Group

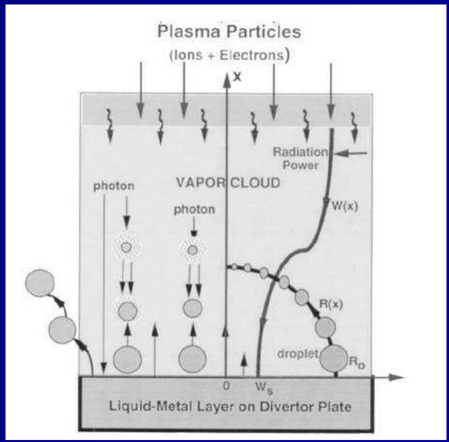
Overview

- Need for an ELM plasma simulator
- Phase I proof-of-concept conical theta pinch ELM simulator
- Scaling to ITER ELMs in Phase II
- Phase II-III, ELM plasma simulation user facility

Why Study ELMs?

- Why do we need this facility?
- Vapor barrier/macro particle formation
- Test plasma-material interaction physics
- Augment and enhance existing US PFC programs
- Future development base



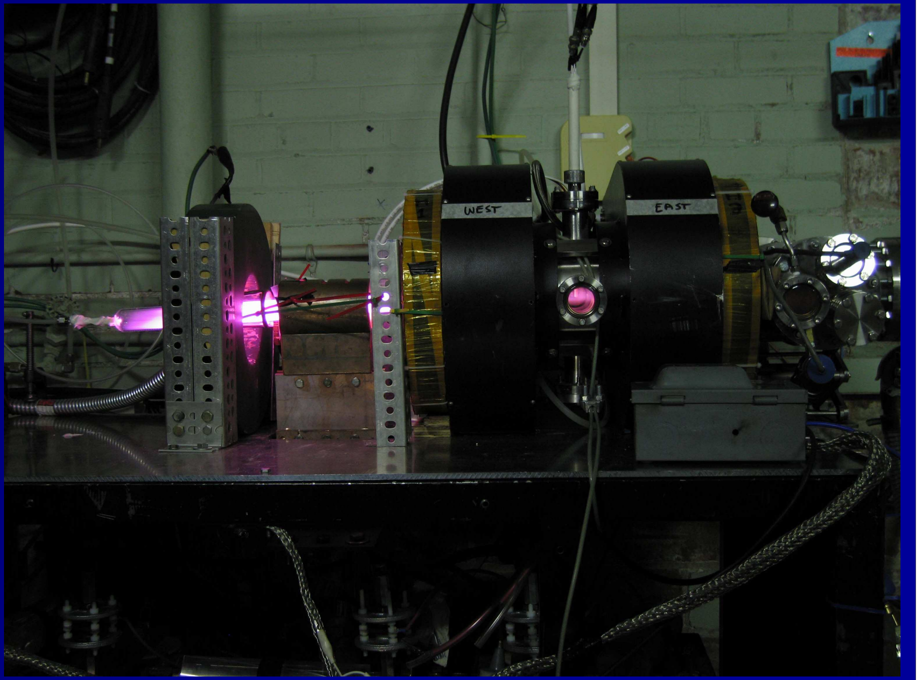


Fits into US Contribution to ITER

- The NEED
  - Advantageous tokamak H-modes accompanied by ELMs
  - Apples-to-apples measurement of ELM plasma material interactions is desired
  - Experimental facility for high-fidelity ELM plasma simulation facility is needed
- Opportunity
  - Complete PFC characterization suite including accurate ELM plasma simulation
- Sandia-Albuquerque has e-beam cyclic high-heat flux and lifetime testing – accurate thermal loading and profile of ELMs
- Argonne modeling for ELM plasma surface interactions
- UCSD is a beryllium mixed material test bed and steady-state plasma exposure tests
- UIUC completes picture with ELM plasma simulation facility
  - Thermal Cycling
  - ELM event physics
  - Steady-state divertor plasma loading
  - Divertor ELM particle loading and erosion

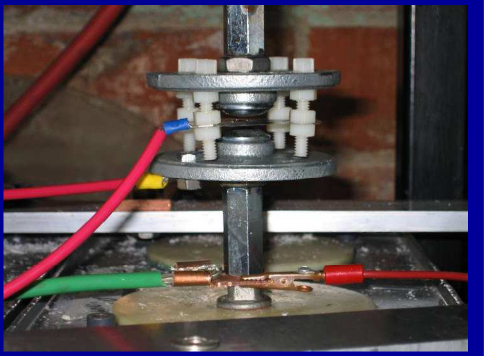
Phase I Facility

- Quick and inexpensive proof of concept
  - Use a conical theta pinch to increase density and temperature of plasma
  - Use ringing PFN to get multiple pinches to simulate what an ELM looks like
  - Use multiple ringing PFNs to achieve ELM durations
  - Translate plasma into a target region with strong magnetic field



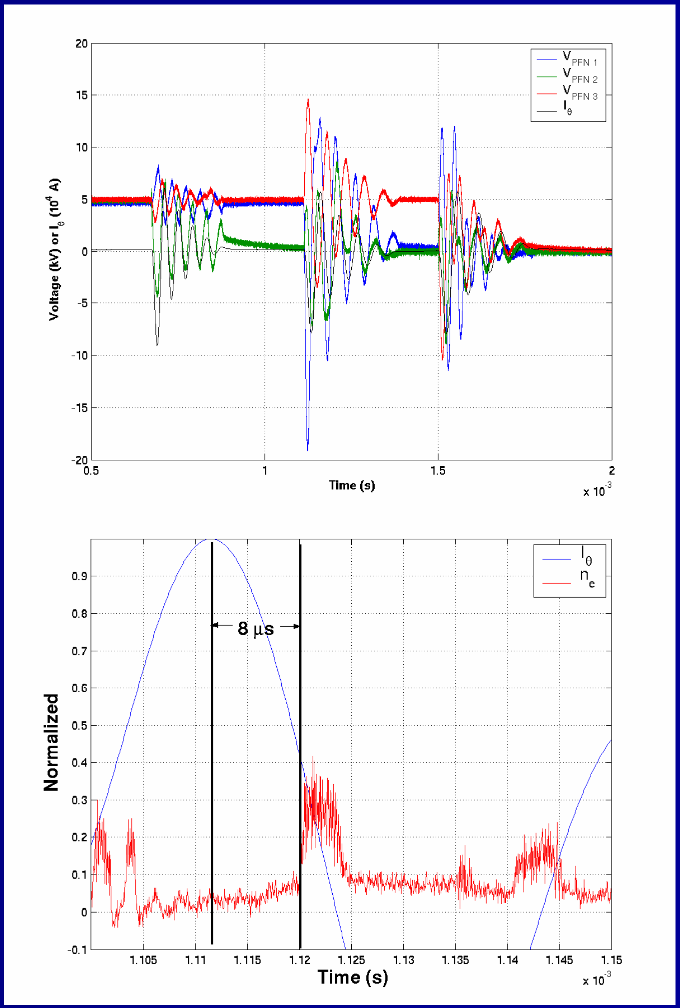
On a Phase I Budget

- Largely built with scrap and home-made equipment
  - Existing coil remachined to conical interior
  - Miscellaneous vacuum equipment
  - Left-over power supplies
  - Home-made trigger circuits
- A little help from e-bay, Starfire equipment and some new equipment
  - Maxwell trigger delays
  - Spectrometer
  - High-voltage probes
  - Glass pinch tube



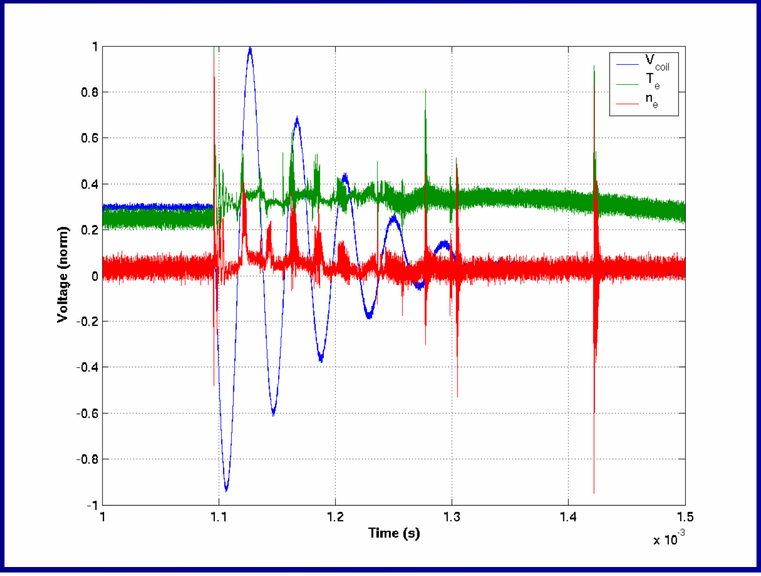
Phase I – Pulse Length/Structure

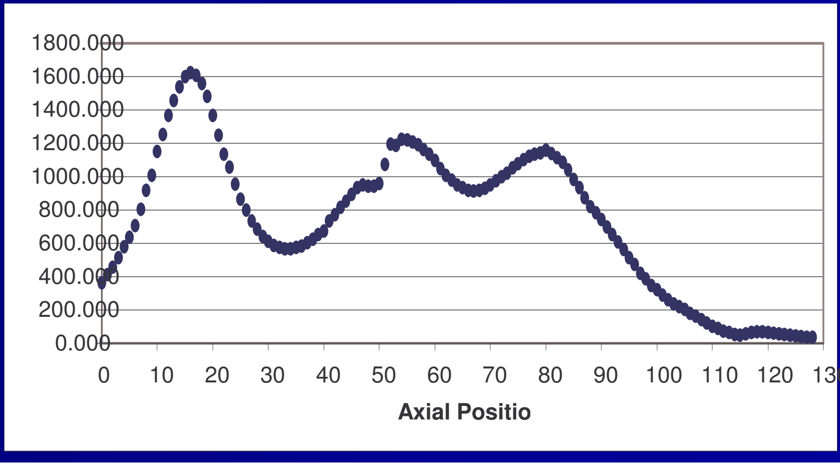
- Multiple pulses To achieve ELM envelope
  - 0.1 to 1 msec time scale with primitive switching
  - Easily improved with better switching (clamping of pulse tail)
- Plasma blob subfrequency
  - ~10-100 microseconds
- Plasma blob transport
  - Translation onto target
  - Velocity ~5X10^{4}m/s



Density and Temperature

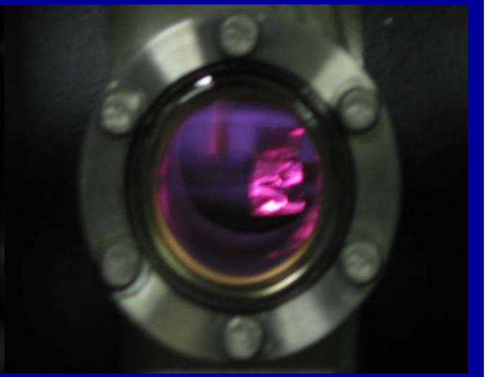
- Density Scaling
  - Density ~$5X10^{17}/m^3$ at 5kV (0.69 kJ)
  - Measured $2X10^{18}/m^3$ at 10kV (2.75 kJ)
- Temperature Scaling
  - Measured ~25eV
- Magnetic Fields
  - 1-kG level Steady State
  - 1-Tesla pinch field
- Approaching NSTX level ELMs in Phase I

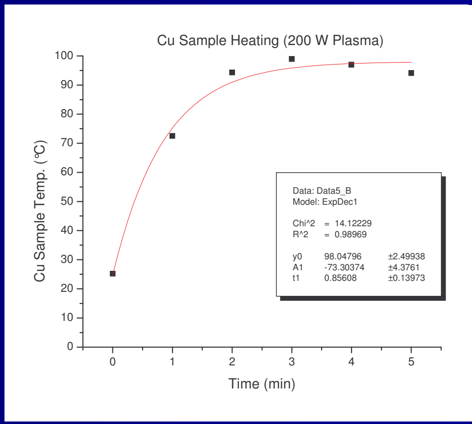


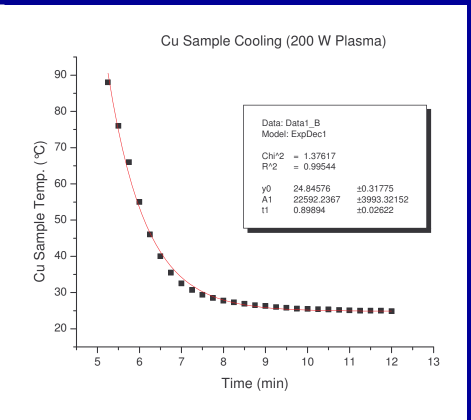


Thermocouple Heating

- Target Plate
- Insulated thermocouple embedded in copper foil
- Temperature rise due to RF plasma has been measured
- Provides means of confirming heating estimates from TLP measurement







Calorimetry Verification of TLP

- Temperature rise measurements confirm TLP Plasma measurements
- Both indicate ~0.5W plasma heating on copper plate with only target helicon plasma present

Thermal Calculation :

$$m \cdot C_p \cdot (T - T_{initial}) = (\dot{Q}_{in} \cdot t) - k \cdot (T - T_{final})$$

$$\dot{Q}_{in} = \frac{(m \cdot C_p + k) \cdot (T_{final} - T_{initial})}{t}$$

$$m = 0.341\, g$$

$$C_p = 0.385\, J / g \cdot K$$

$$k = 1.1\, J / K$$

$$t = 180 \sec$$

$$P_{thermal} = \dot{Q}_{in} = 0.5 W$$

Plasma Calculation :

$$P_{Plasma} = \Gamma \cdot A \cdot T_e$$

$$= \frac{n \cdot \bar{v}}{4} \cdot A \cdot T_e$$

$$n = 2 \cdot 10^{16}\, m^{-3}$$

$$T_e = 3.5\, eV$$

$$A = 1\, cm^{-2}$$

$$P_{Plasma} = 0.35 W$$

Phase I Summary

- Phase I effort provided good proof of concept
  - Demonstrated subfrequency with ringing PFN
  - Demonstrated appropriate, adjustable effective pulse duration using sequentially-fired PFNs
  - Demonstrated plasma heating and translation to target

Scaling To ITER

- Expected ITER ELM Conditions (and desired ELM simulation parameters)
  - ~ $10^{19}/m^3$
  - ~1 keV temperatures
  - ~1 ms duration
  - ~5 Tesla B fields (DC)
  - ~10MJ/m^2
- Present conditions in ELM simulator
  - $2X10^{18}/m^3$
  - ~25eV
  - 1 ms duration
  - 0.1 Tesla B fields (DC)
  - ~10kJ/m^2

ELM Parameter	ITER	NSTX	UIUC (present)
Power Loading	~10 MJ/m^2	<1 MJ/m^2	10 kJ/m^2
ELM Event Frequency	~1-10 Hz	10-20 Hz	Single shot
Total ELM Duration	~0.1-1 ms	~1 ms	1 ms
Blob Subfrequency	~10-100 kHz	~10 kHz	10 kHz
Temperature During ELM (~$T_{pedestal}$)	1-2.5 keV	100 eV	20-40 eV*
Density During ELM (~$n_{pedestal}$)	~$10^{19}/m^3$	~$10^{19}/m^3$	$10^{18}/m^{3*}$
Divertor Field Strength (~B_t)	~1-5 T	~0.5 T	0.1 T

Theta Pinch Scaling

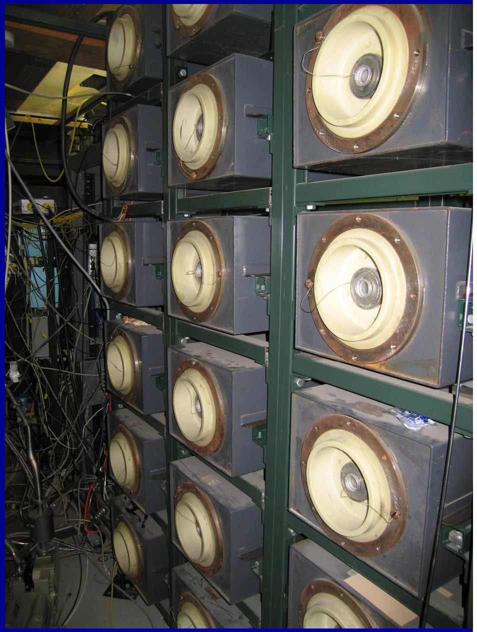
- Ideal Case
  - For ideal magnetic-kinetic pressure balance (perfect coupling), only ~700 Gauss is required to contain 1-keV $10^{19}/m^3$ plasma
  - Coupling efficiency depends on dI/dt (bank inductance) and magnetic diffusion time (preionization source density and temperature)
  - Therefore, field in pinch region is already adequate
- Energy Scaling
  - Crude scaling: Energy flux out scales linearly with bank energy
  - Based on this scaling and Phase I measured results, ~2MJ/m^2 could be achieved with 250kJ bank (200+ times the energy input)
  - Present pinch field (4-10 kGauss with 10kV on bank) would be more than enough if coupling were better
  - Crude scaling neglects improvements to coupling – power levels on target could be even better.

Theta Pinch Scaling (cont)

- Coupling Improvement – dI/dt Scaling
  - Phase I current rise times are ~13-17μs – very long compared to an estimated magnetic diffusion time of ~1 μs.
  - Decreased bank inductance (~20nH/capacitor compared to ~500nH/capacitor) will lead to a rise time less than 1/10th present value.
  - dI/dt can increase further if capacitors are connected in parallel (likely with 2 μF capacitors), and operated at higher voltage (60 kV instead of 10kV)
  - Magnetic diffusion time can be increased with improved preionization source.
- With pulse rise time near or less than the magnetic diffusion time, coupling should more closely resemble ideal case than linear case, and a factor of 10 or greater improvement can be expected

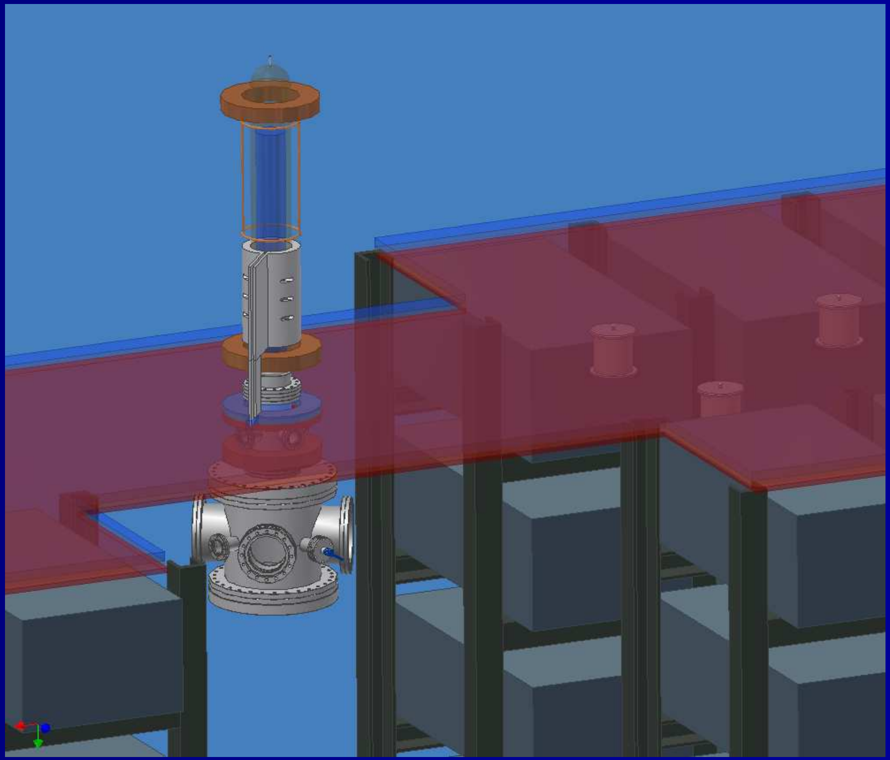
Phase II – ITER ELM Simulation

- Scale-up to reach ITER ELM demo
  - 250 kJ bank
  - 56 60-kV 2-μF capacitors (~20nH inductance each)
  - Bank divided into 4 independent PFNs
- Expected Phase II plasma parameters
  - Density ~$10^{19}/m^3$
  - Temperature ~1keV
  - Duration ~0.5-1ms
- An ITER ELM simulator can be built at Illinois



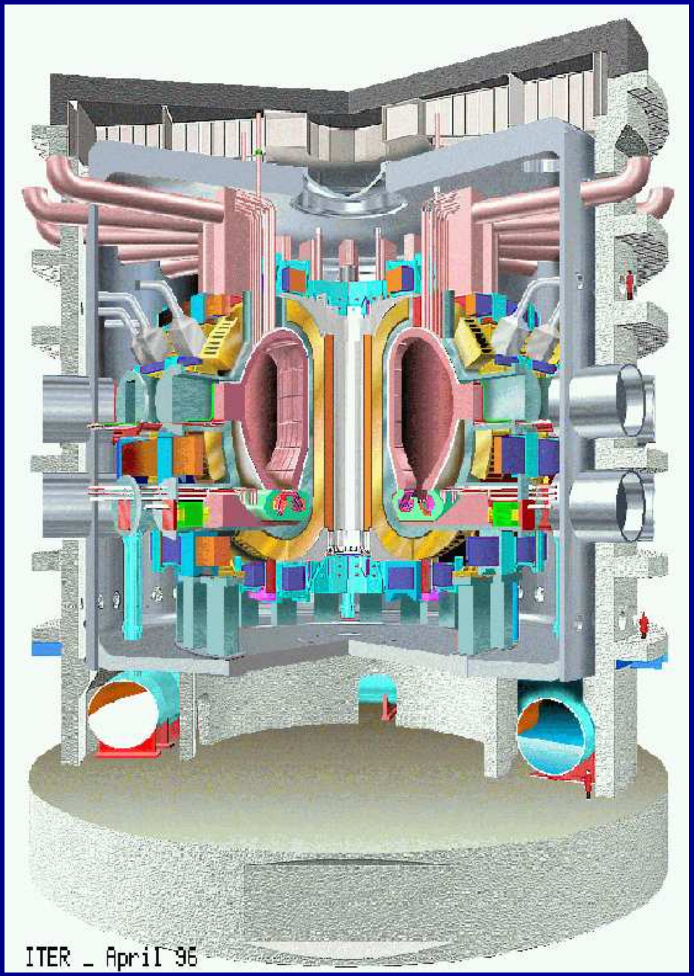
Phase II Plan

- Use Installed base at University of Illinois
- Utilize existing capacitor bank and set it up for 60kV operation at 250kJ.
  - Significant undertaking to build transmission line system.
  - Some transmission lines exist, but division of bank needed
  - Switching is a challenge at 60 kV
- New coil, magnet assembly and other components.
  - 5 Tesla field is also challenging
  - Will likely be pulsed (slowly)
- Two-year effort to demonstrate ITER-level ELM events
- Work toward Phase III ELM plasma test facility



Resources Almost There

- Joint Investment by
  - University of Illinois
  - Starfire Industries
  - STTR Program
  - DOE
- In-kind expenses already committed pending Phase II success
  - University of Illinois
  - Starfire Industries
- Plan for Phase II-III



Commercial Model

- ELM Test Facility in US
  - National Labs
  - Academia
  - Private Industry
  - International Developers
- University of Illinois is an ideal location
  - Center for Microanalysis of Materials (DOE user facility) – mutually complementary with ELM test facility
  - Centrally located
  - Existing equipment and know-how

Summary

- Phase I successfully demonstrated conical theta pinch ELM simulator concept
- Phase II ITER ELM demo – Phase I data and scaling support ITER ELM simulation is possible with reasonable investment
- Good path toward ELM plasma simulator user facility after Phase II demo (Phase III)

Questions/Contact

Robert Stubbers

Starfire Industries LLC

rstubbers@starfireindustries.com